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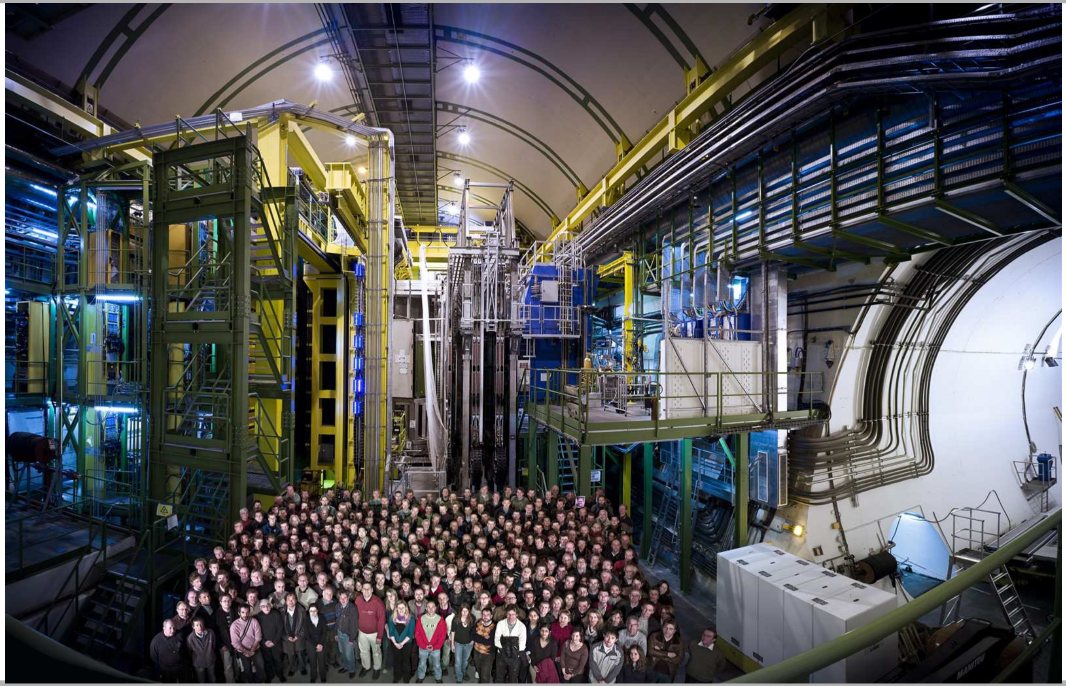
Exotic meson studies at LHCb

M. Kreps on behalf of the LHCb Collaboration

Physics Department



Introduction

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Volume 8, number 3 PHYSICS LETTERS 1 February 1964

A SCHEMATIC MODEL OF BARYONS AND MESONS *

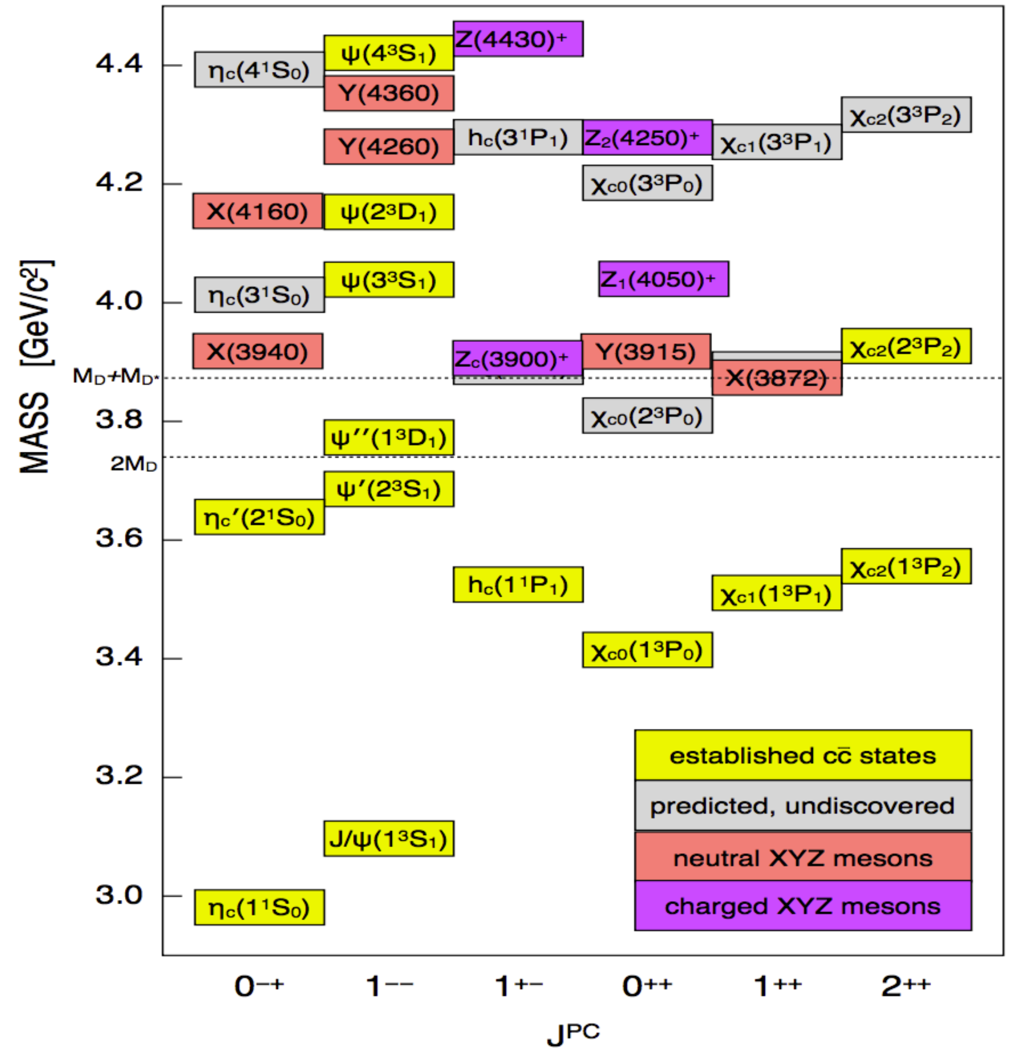
M. GELL-MANN
California Institute of Technology, Pasadena, California

Received 4 January 1964

We then refer to the members $u^{\frac{2}{3}}$, $d^{-\frac{1}{3}}$, and $s^{-\frac{1}{3}}$ of the triplet as "quarks" 6) q and the members of the anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations $(q\,q\,q)$, $(q\,q\,q\,q\,\bar{q})$, etc., while mesons are made out of $(q\,\bar{q})$, $(q\,q\,\bar{q}\,\bar{q})$, etc. It is assuming that the lowest

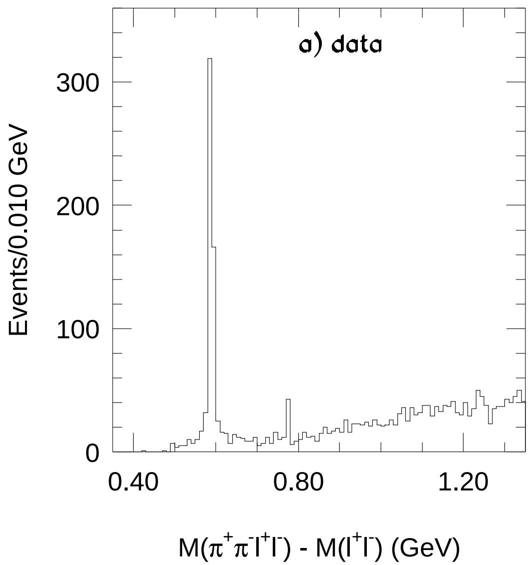
- We think of hadrons as $q\bar{q}$ or qqq
- But there is nothing preventing other combinations
- Can we find
  - molecule
  - tetraquark
  - your other favourite choice

arXiv:1403.1254



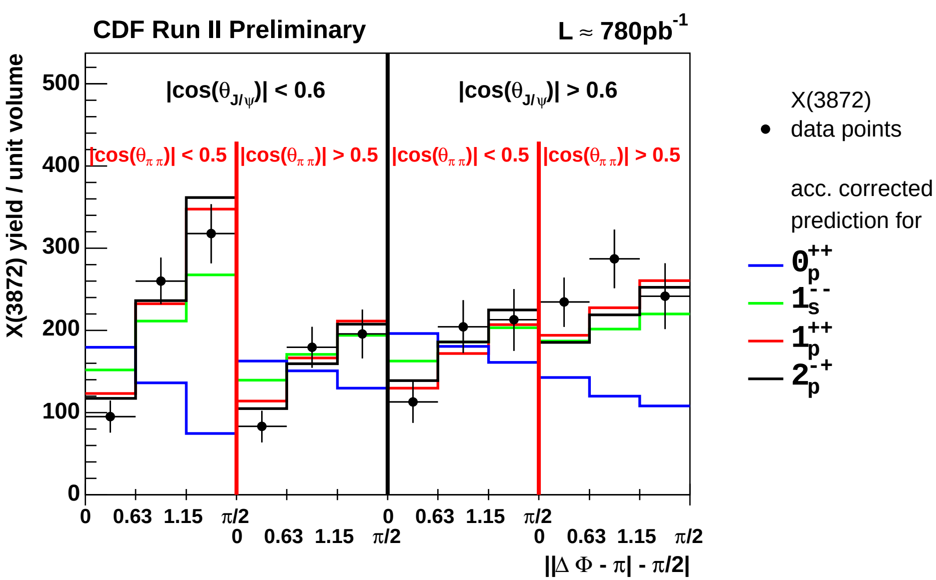
$X(3872)$ enigma

PRL 91, 262001

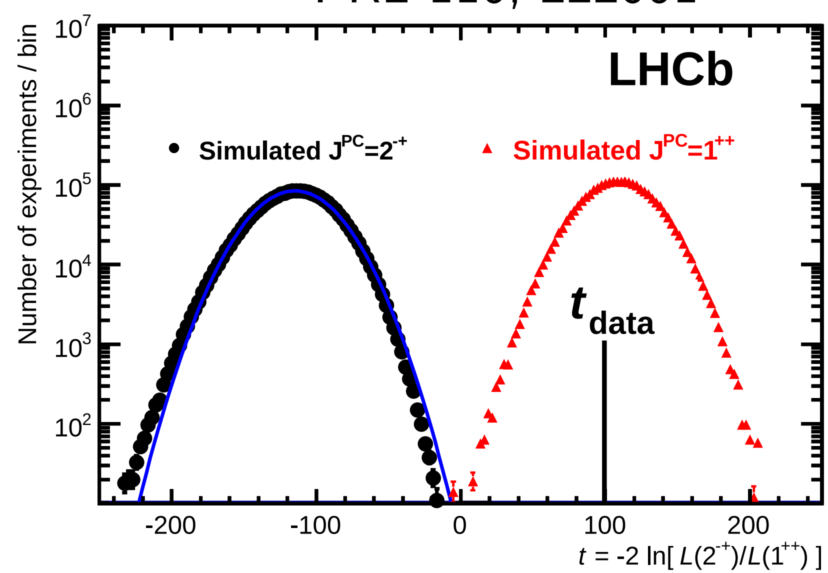


- Discovered in 2003 by Belle
- Huge number of results available
- Quantum numbers $J^{PC} = 1^{++}$
- Nature of $X(3872)$ still unclear
- Today radiative decays

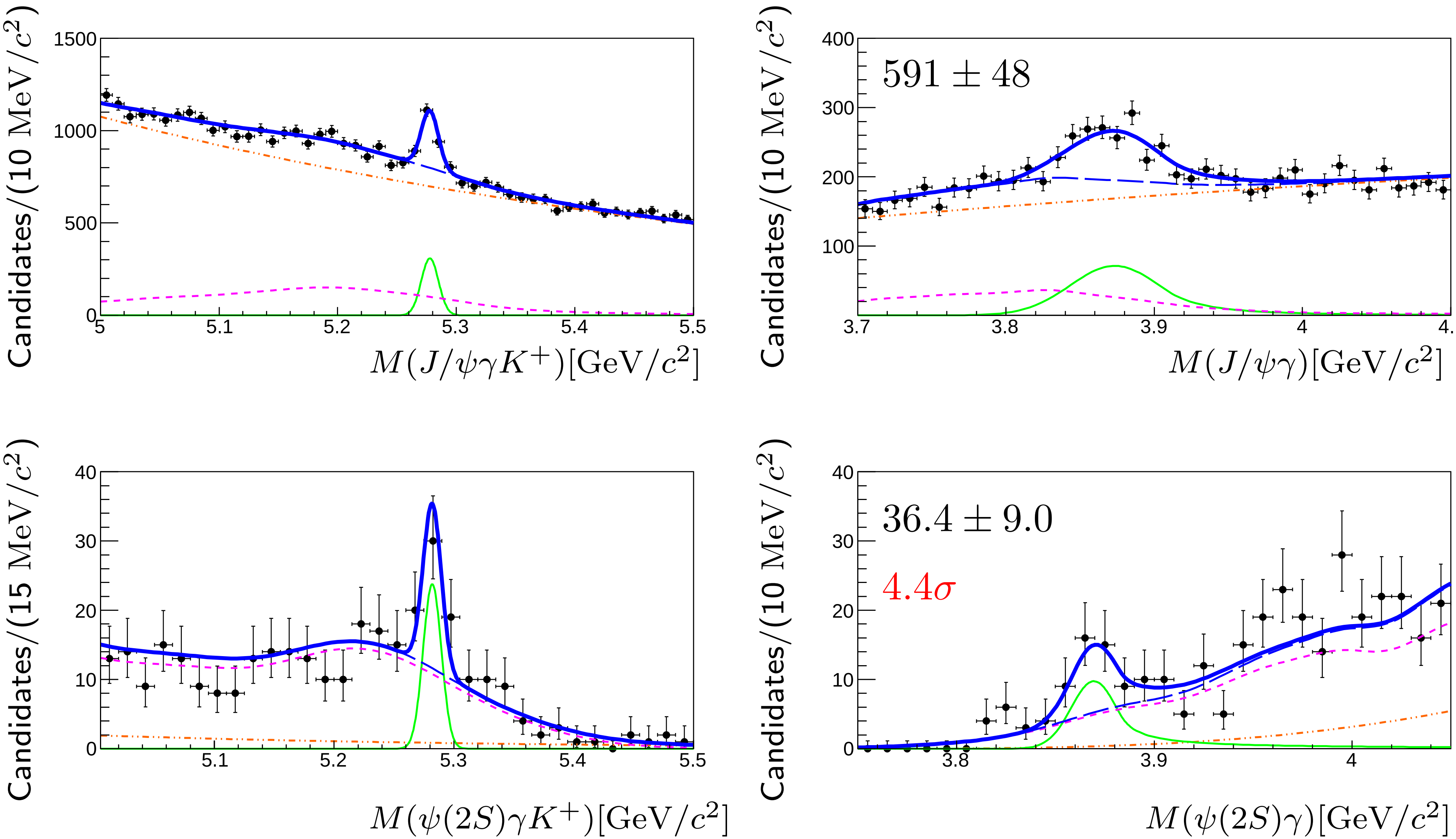
PRL 98, 132002



PRL 110, 222001



$\mathbf{X(3872)} \rightarrow \psi\gamma$



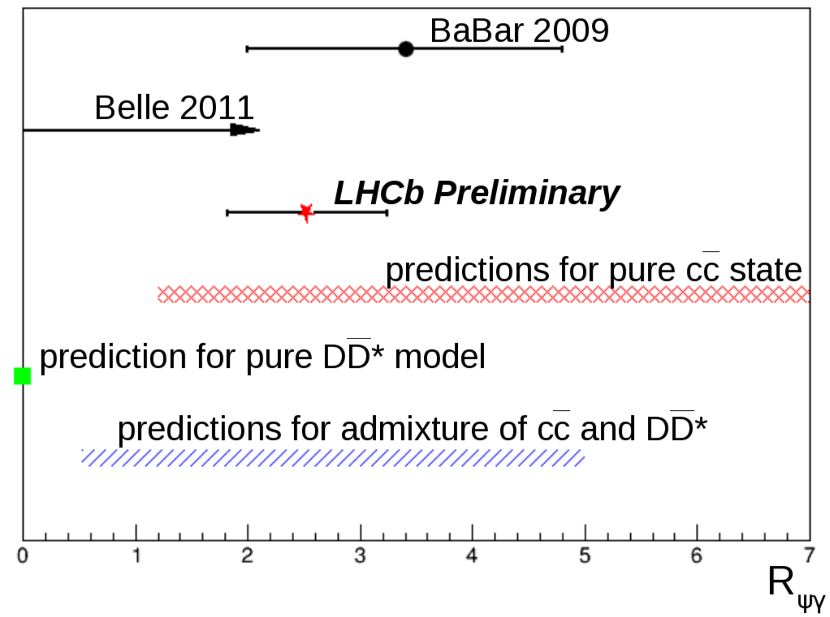
arXiv:1404.0275

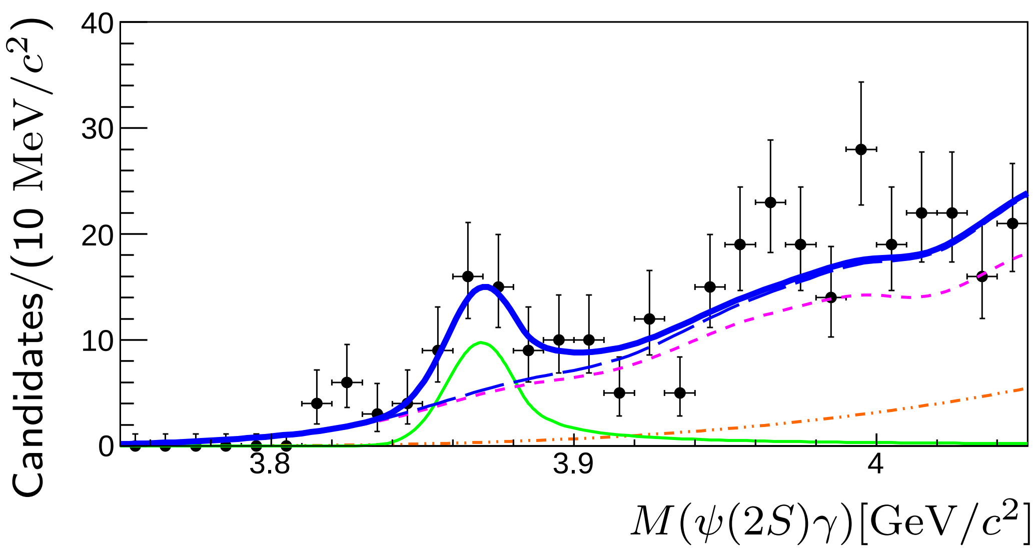
$\mathbf{X(3872)} \to \psi\mathbf{(2S)}\gamma$

- We measure

$$R = \frac{\mathcal{B}(X(3872) \to \psi(2S)\gamma)}{\mathcal{B}(X(3872) \to J/\psi\,\gamma)} = 2.46 \pm 0.64 \pm 0.29$$

- Compare to theory for different interpretations
  - Clear inconsistency with pure molecule
  - Pure $c\bar{c}$ or mixture of molecule with $c\bar{c}$ possible

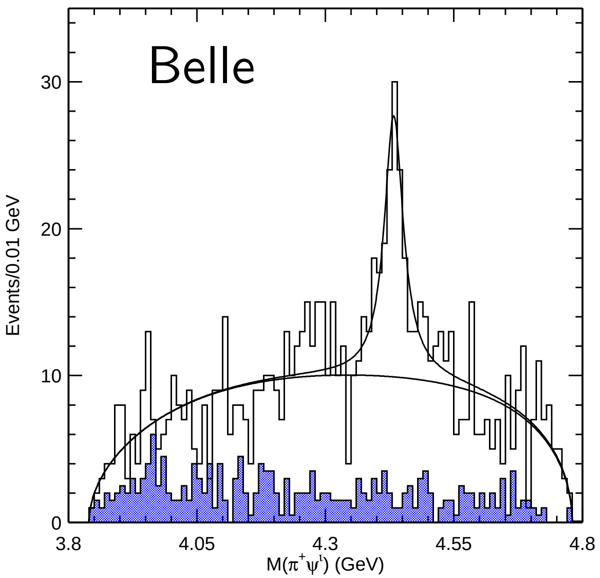




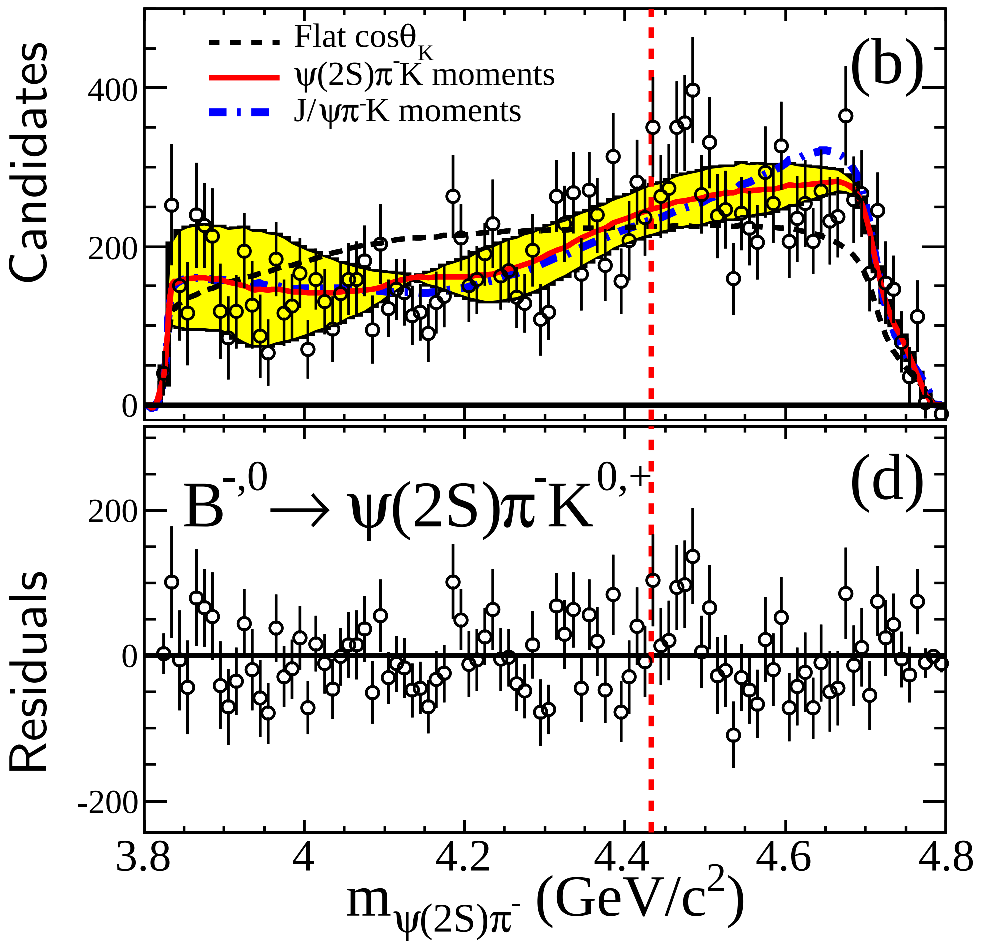
arXiv:1404.0275

$\mathbf{Z(4430)^+}$ history

PRL 100, 142001



PRD 79, 112001



- Seen by Belle, but not Babar
- Data consistent
- Charged state

$\rightarrow$ Cannot be $c\bar{c}$

- Latest Belle result uses 4D analysis
- Is it real and if yes, is it resonance?

$Z(4430)^+$ history

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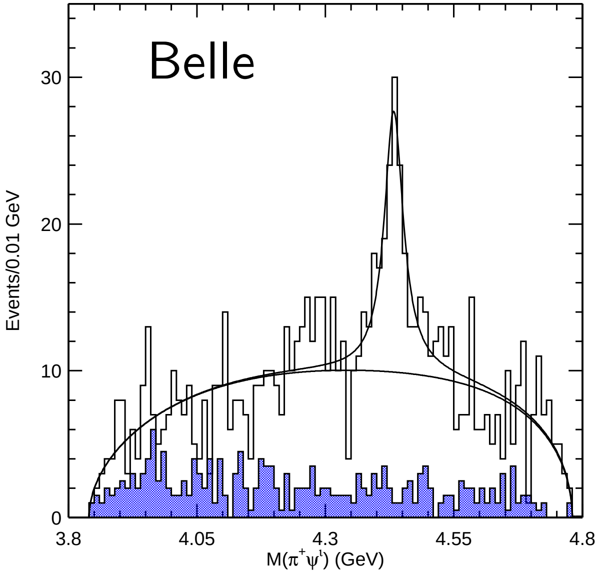
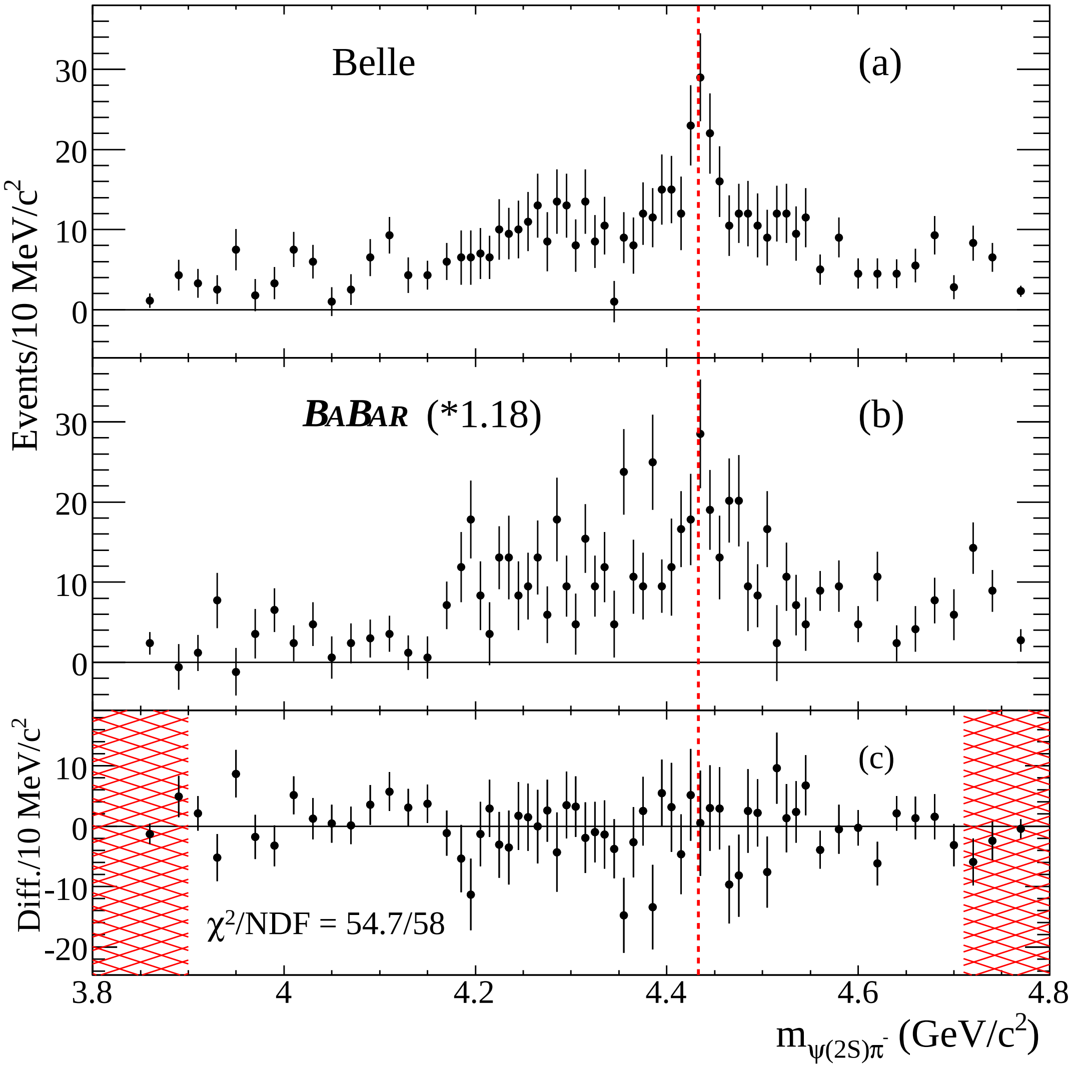
PRL 100, 142001





PRD 79, 112001

- Seen by Belle, but not Babar
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$\rightarrow$ Cannot be $c\bar{c}$

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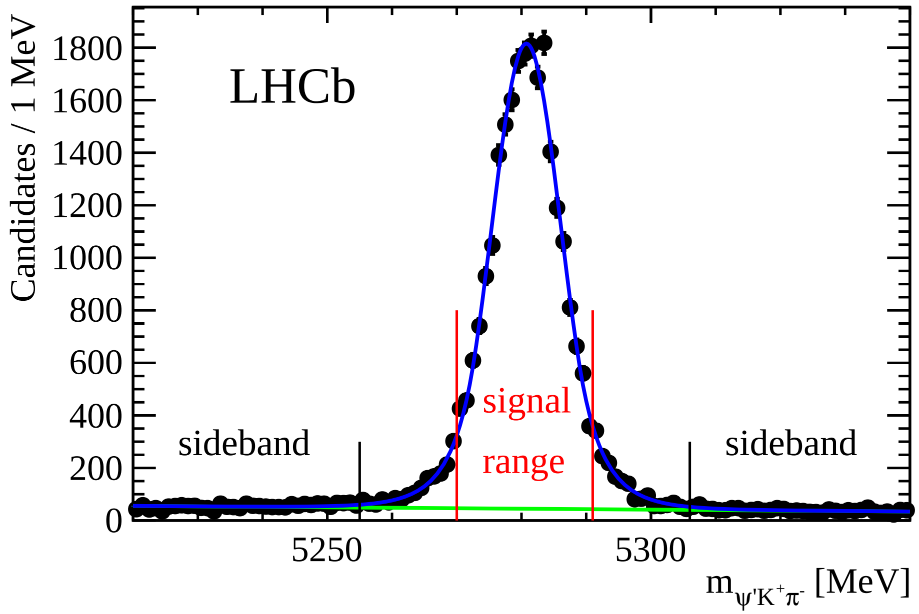
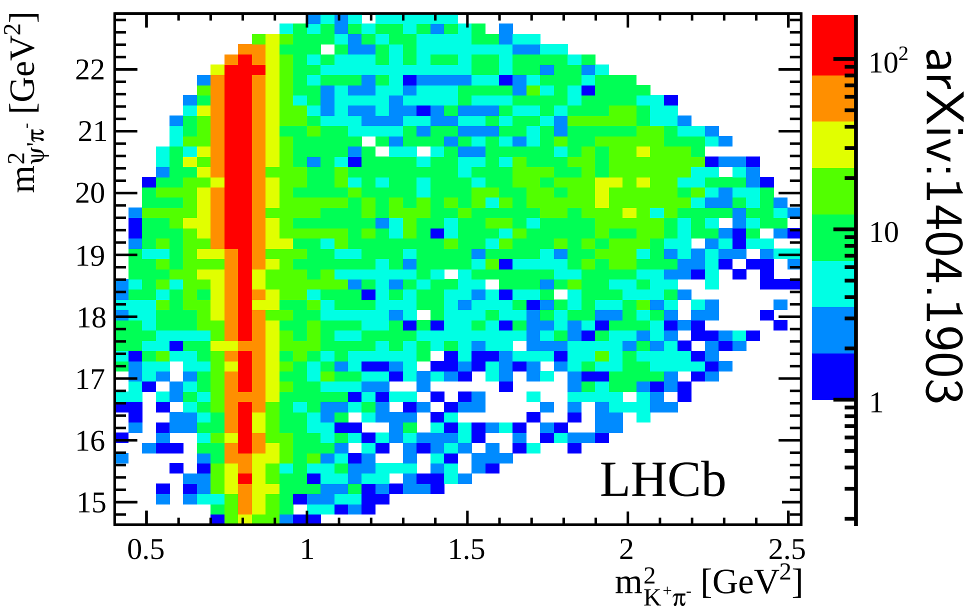
Data sample

- Use $B^0 \to \psi(2S)K\pi$ decays
- Large statistics (> 25k), about 10 times what B-factories had
- Very clean signal, background $4\,\%$ of events (about 8% at B-factories)
- Perform both model-independent analysis (BABAR) and amplitude fit (Belle)



Only 2 out of 4 dimensions

$K^*(892)$ $K^*_J(1430)$



Model independent method

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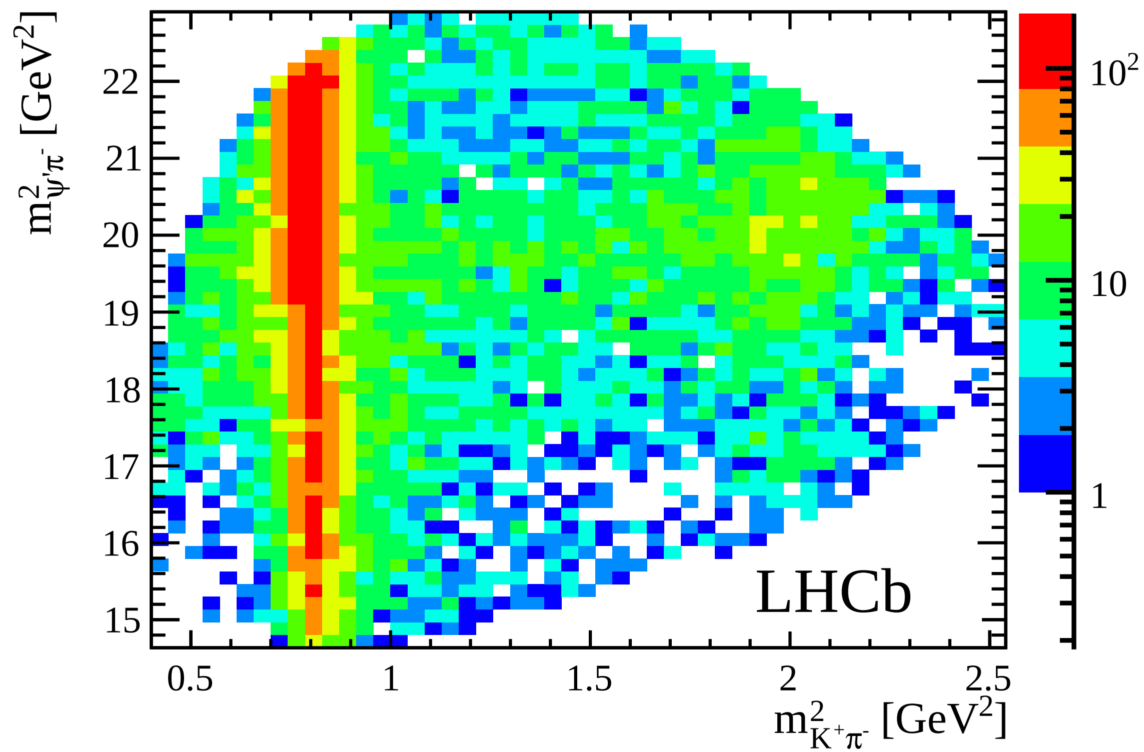
arXiv:1404.1903



- Look to $\cos(\theta_K)$ in bins of $K\pi$ mass
- Allows to find out which spins contribute

$$\sum_i \frac{1}{\epsilon_i} P_l(\cos\theta_{Ki})$$

- Take only moments corresponding to $J \leq 2$
- Construct Dalitz plot and project on $\psi(2S)\pi$ axis

- Test whether contributions in $K\pi$ system can describe data
- Do not impose specific model for resonances

$\rightarrow$ Model independent test

Model independent result

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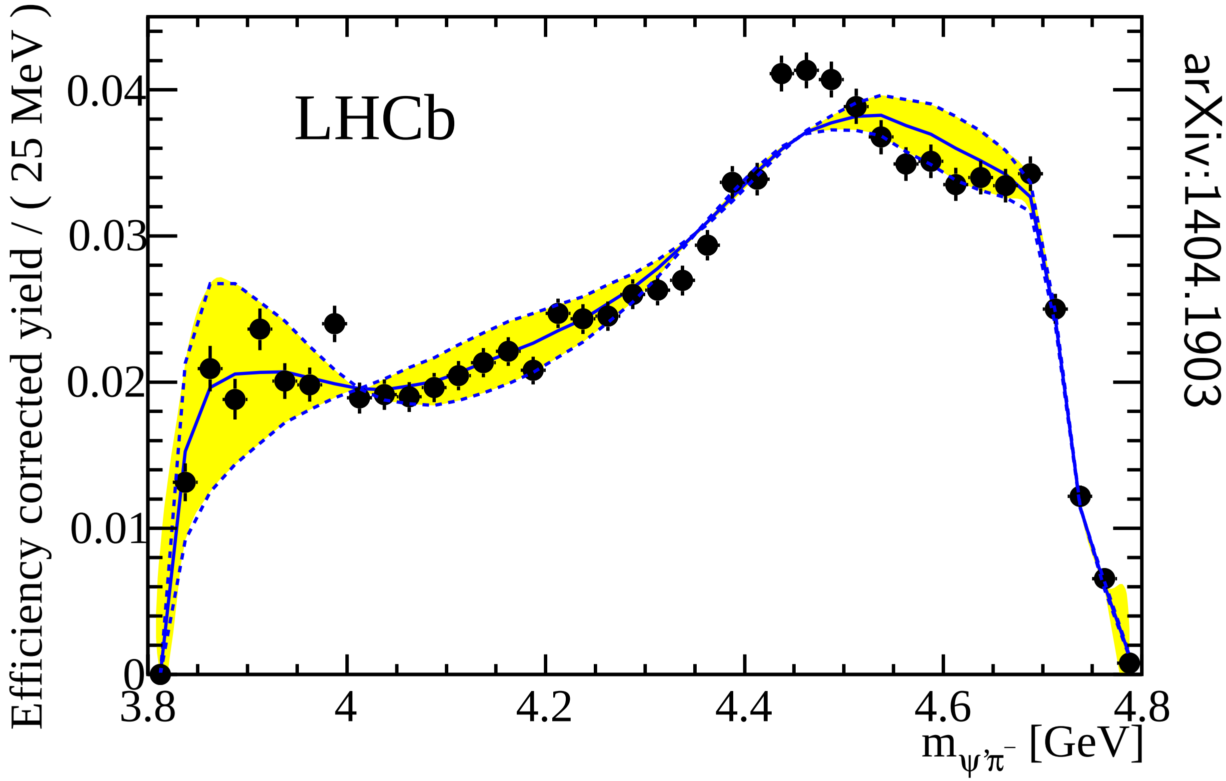

- Clearly, pure kaon resonances cannot explain $M(\psi(2S)\pi)$ spectrum
- Understanding details difficult
  - Resonances in $\psi(2S)\pi$ will contribute to $K\pi$ and its moments
  - Any fit to $\psi(2S)\pi$ on top of reflections neglects interference between two axes

Amplitude analysis

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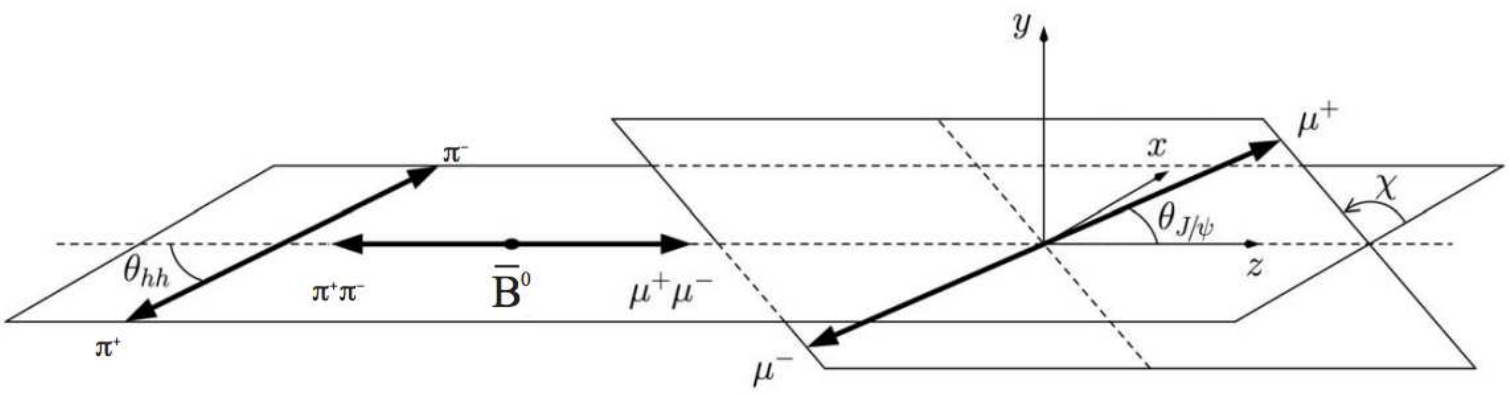

- Full 4D amplitude analysis
- Amplitude

Rotation between helicity frames

$$|M|^2 = \sum_{\Delta\lambda_\mu} \left| \sum_{\lambda_\psi} \sum_k A_{k,\lambda_\psi}(\Omega|m_{0k},\Gamma_{0k}) + \sum_{\lambda_\psi^Z} A_{Z,\lambda_\psi^Z}(\Omega^Z|m_{0Z},\Gamma_{0Z}) e^{i\Delta_\mu \alpha} \right|^2$$

- Mass described by relativistic Breit-Wigner
- Angular part using helicity formalism
- Imposes model how invariant mass distribution should look like

Only K^* resonances

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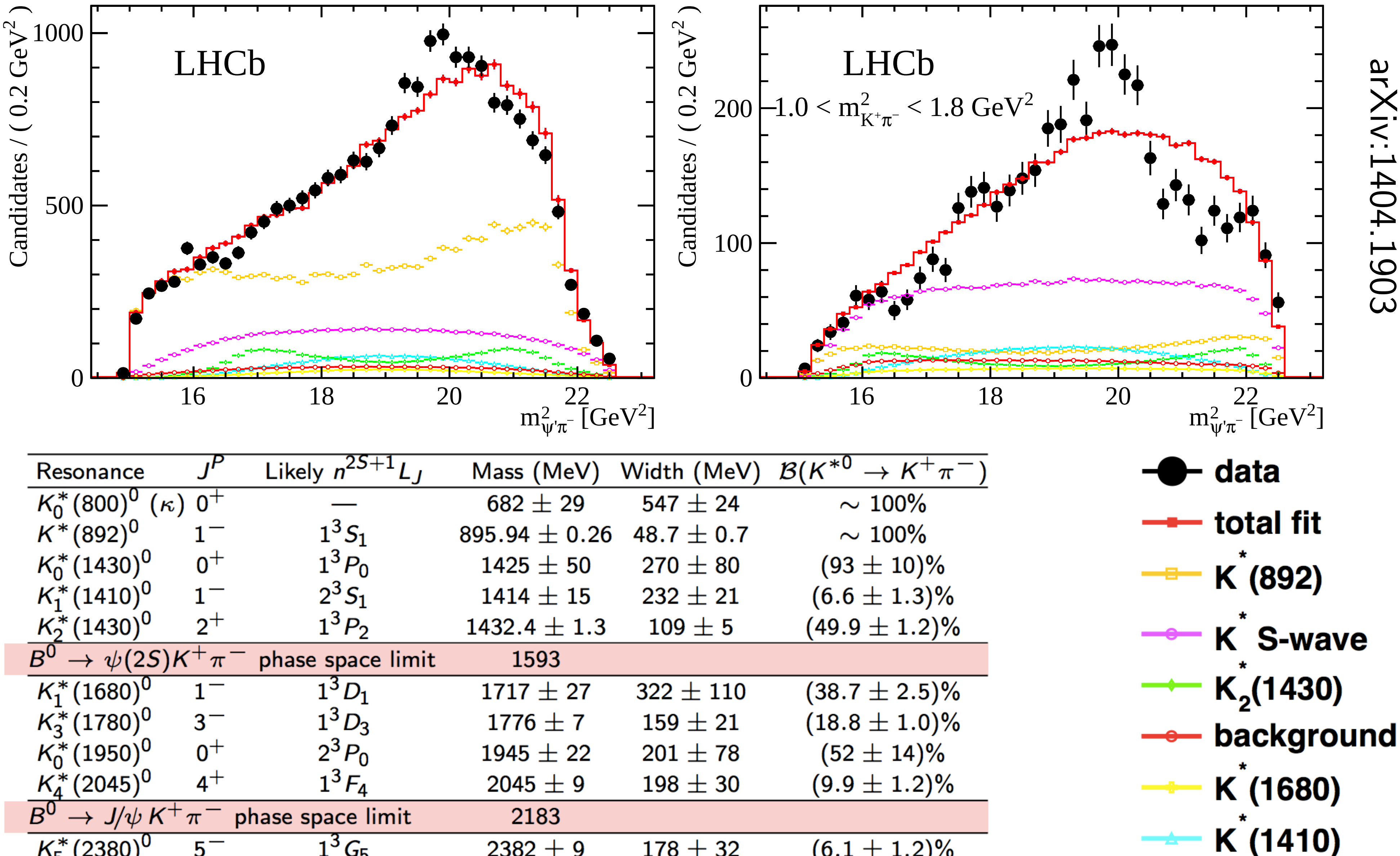
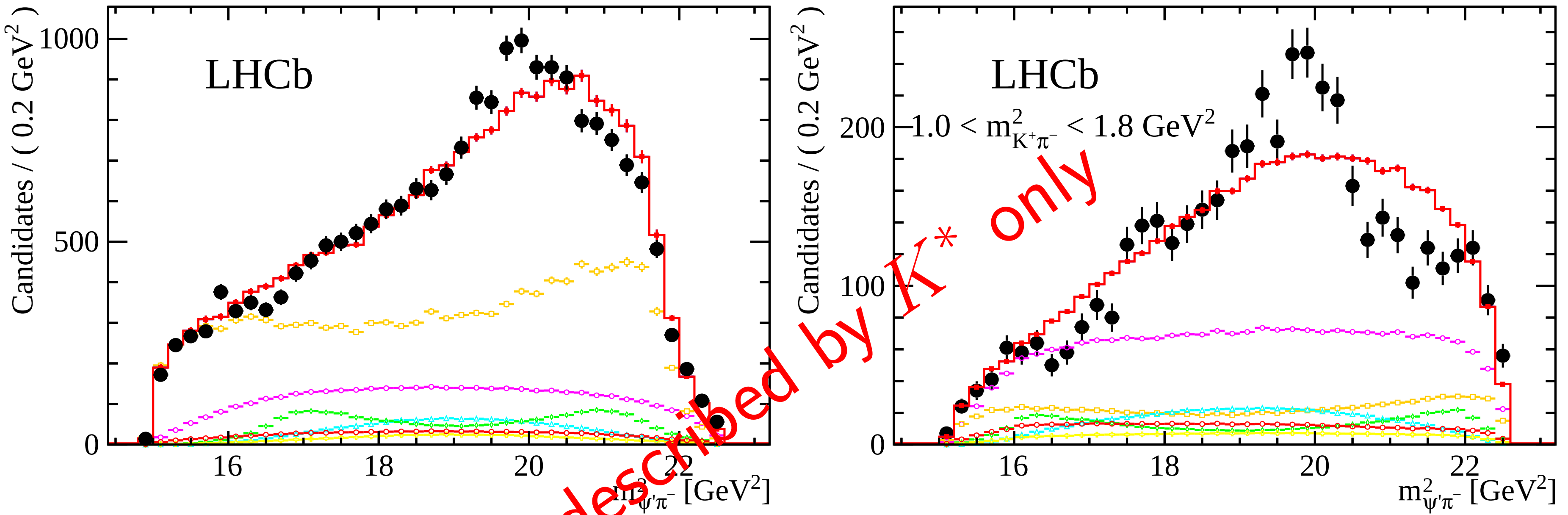


arXiv:1404.1903

Resonance	J^P	Likely $n^{2S+1}L_J$	Mass (MeV)	Width (MeV)	$\mathcal{B}(K^{*0} \to K^+\pi^-)$
$K_0^*(800)^0$ (κ)	0^+	—	682 ± 29	547 ± 24	$\sim 100\%$
$K^*(892)^0$	1^-	1^3S_1	895.94 ± 0.26	48.7 ± 0.7	$\sim 100\%$
$K_0^*(1430)^0$	0^+	1^3P_0	1425 ± 50	270 ± 80	$(93 \pm 10)\%$
$K_1^*(1410)^0$	1^-	2^3S_1	1414 ± 15	232 ± 21	$(6.6 \pm 1.3)\%$
$K_2^*(1430)^0$	2^+	1^3P_2	1432.4 ± 1.3	109 ± 5	$(49.9 \pm 1.2)\%$
$B^0 \to \psi(2S)K^+\pi^-$ phase space limit			1593		
$K_1^*(1680)^0$	1^-	1^3D_1	1717 ± 27	322 ± 110	$(38.7 \pm 2.5)\%$
$K_3^*(1780)^0$	3^-	1^3D_3	1776 ± 7	159 ± 21	$(18.8 \pm 1.0)\%$
$K_0^*(1950)^0$	0^+	2^3P_0	1945 ± 22	201 ± 78	$(52 \pm 14)\%$
$K_4^*(2045)^0$	4^+	1^3F_4	2045 ± 9	198 ± 30	$(9.9 \pm 1.2)\%$
$B^0 \to J/\psi K^+\pi^-$ phase space limit			2183		
$K_5^*(2380)^0$	5^-	1^3G_5	2382 ± 9	178 ± 32	$(6.1 \pm 1.2)\%$

Only K^* resonances



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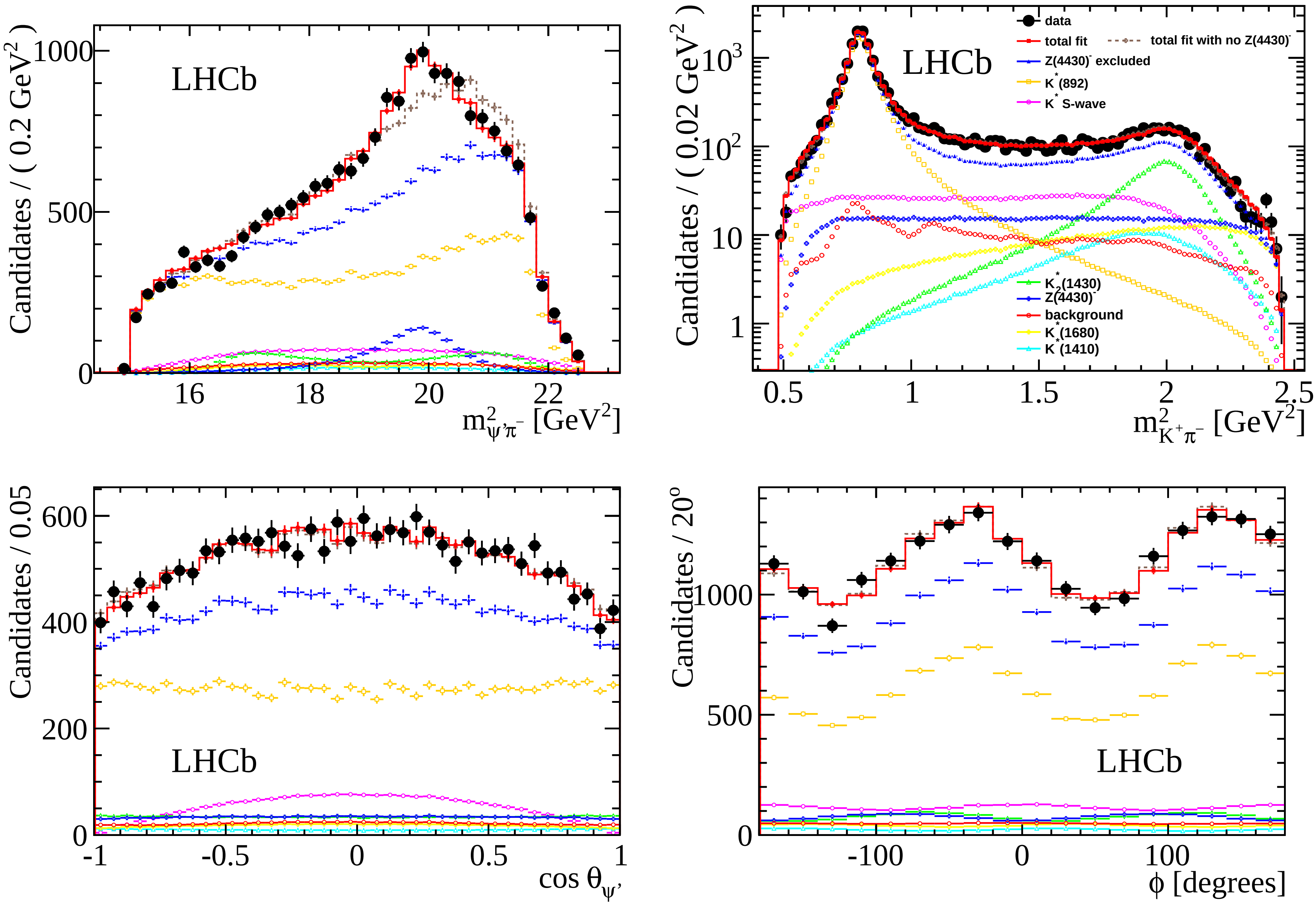
Adding Z^+



arXiv:1404.1903

Dalitz plot slices

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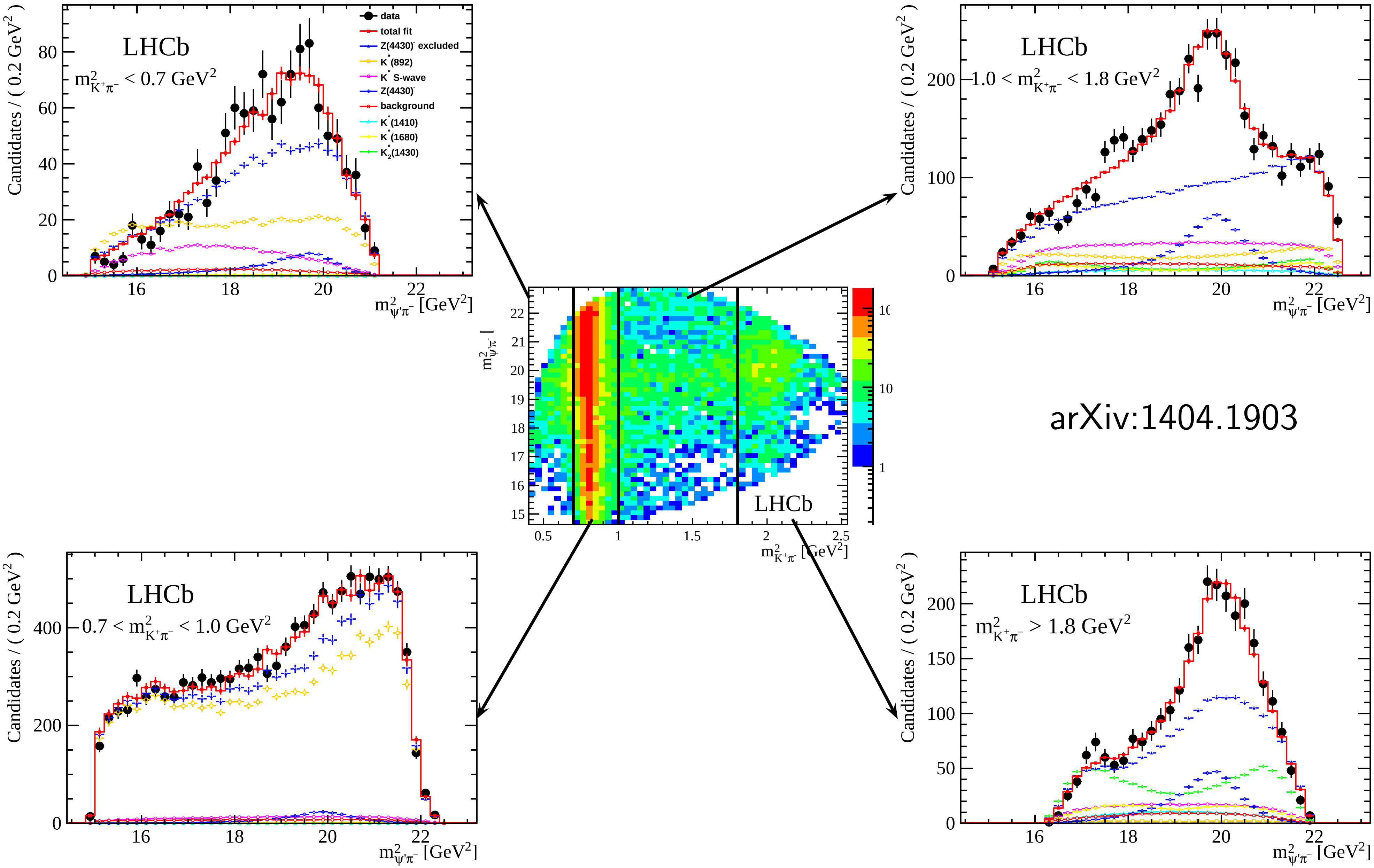
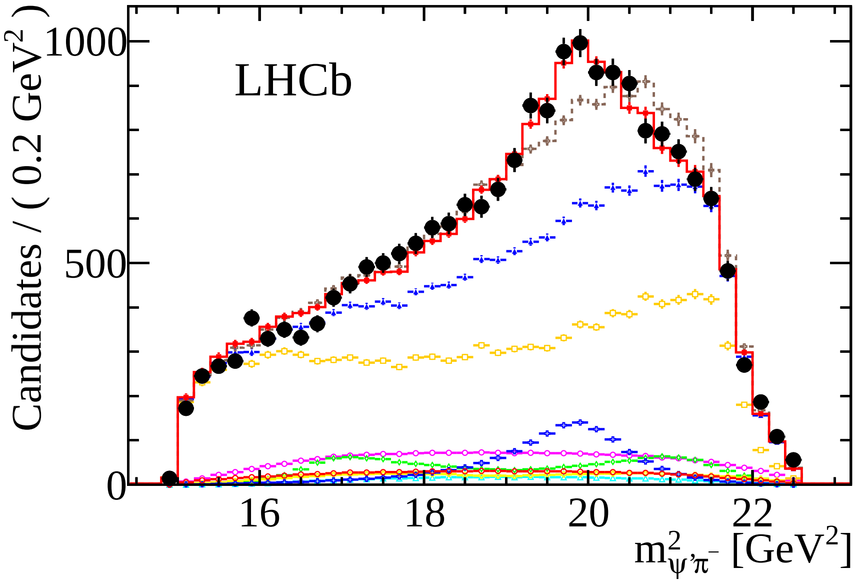


arXiv:1404.1903

Results

arXiv:1404.1903



$M(Z)$	$4475 \pm 7^{+15}_{-25}$ MeV
$\Gamma(Z)$	$172 \pm 13^{+37}_{-34}$ MeV
f_Z	$5.9 \pm 0.9^{+1.5}_{-3.3}$ %
f_Z^I	$16.7 \pm 1.6^{+2.6}_{-5.2}$ %
Significance	$> 13.9\sigma$

- Data are described well with 1^+ $Z(4430)^+$ contribution (χ^2 p-value 12%)
- Parameters extracted consistent with Belle
- Large interference effects seen
- Adding additional K^* resonances to model does not alter conclusion

$Z(4430)^+$ spin

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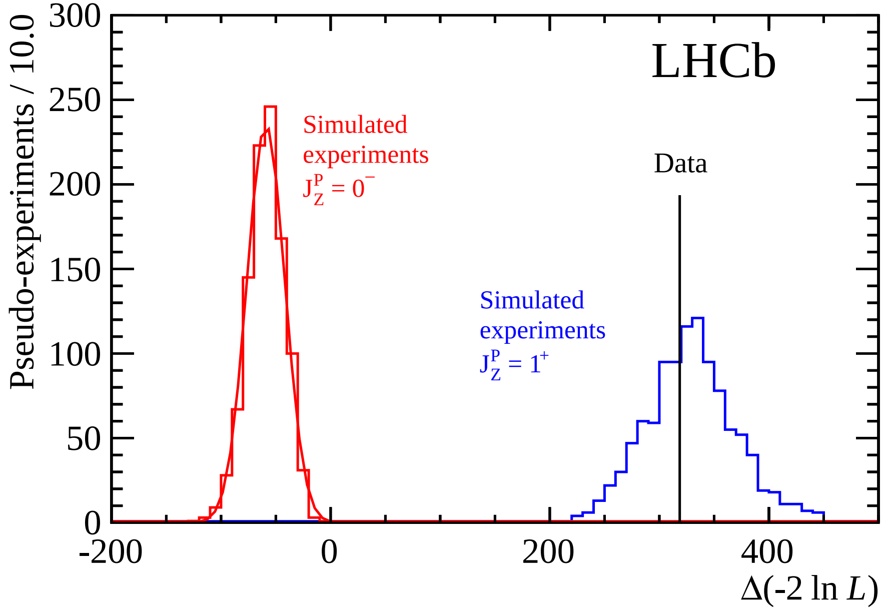
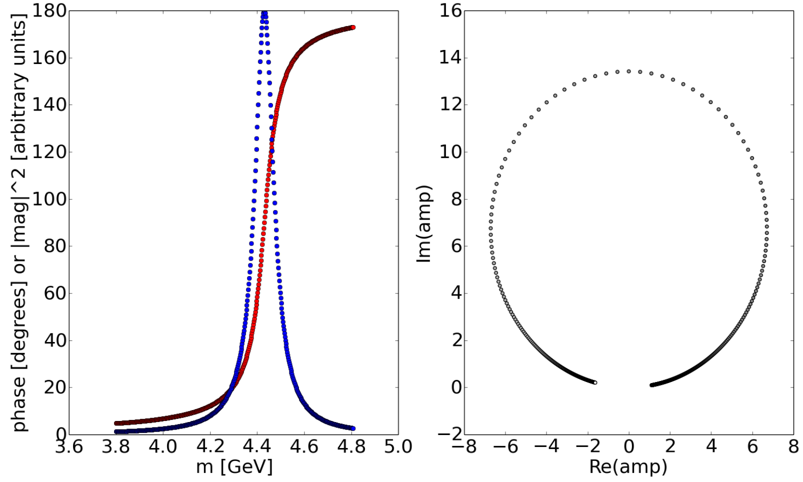
arXiv:1404.1903



Hypothesis	Rejection
0^-	$9.7\,\sigma$
1^-	$15.8\,\sigma$
2^+	$16.1\,\sigma$
2^-	$14.6\,\sigma$

- As we use full kinematic information, we have sensitivity to quantum numbers
- Test spins 0,1 and 2 with both parities
- Based on likelihood ratio
- Quote exclusion based on asymptotic formula (lower bound)
- Verified by simulation
- All rejections relative to 1^+
- $Z(4430)^+$ is 1^+ state without any doubts

Is $\mathrm{Z}(4430)^{+}$ resonance?



- Data are consistent with BW for $Z(4430)^{+}$
- But will they follow if BW is not imposed?
- Change BW in $Z(4430)^{+}$ amplitude to 6 complex numbers in 6 $M(\psi(2S)\pi)$ bins
- Plot resulting amplitude on Argand plot

Is $Z(4430)^+$ resonance?

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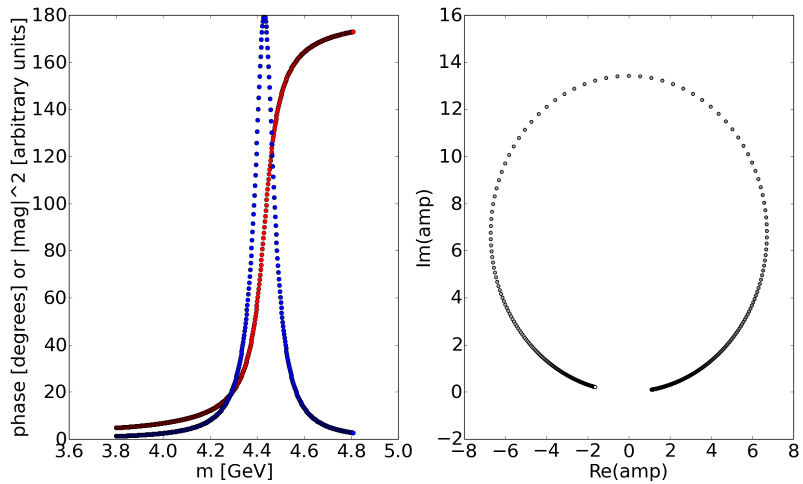

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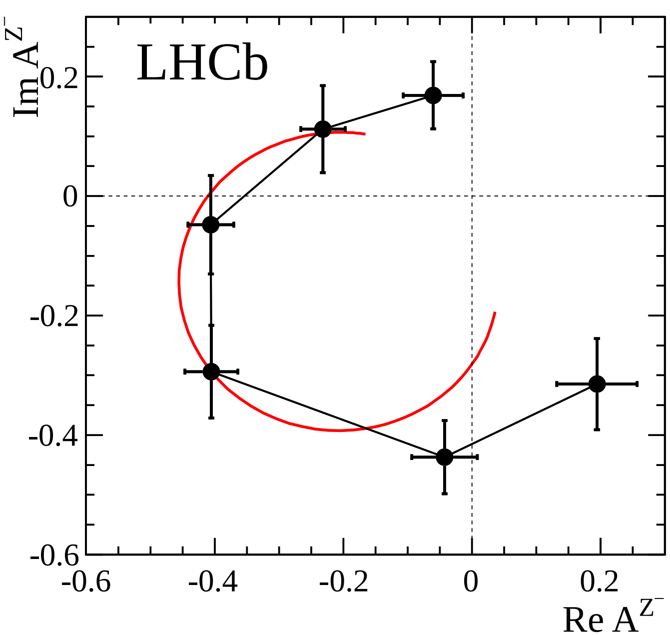
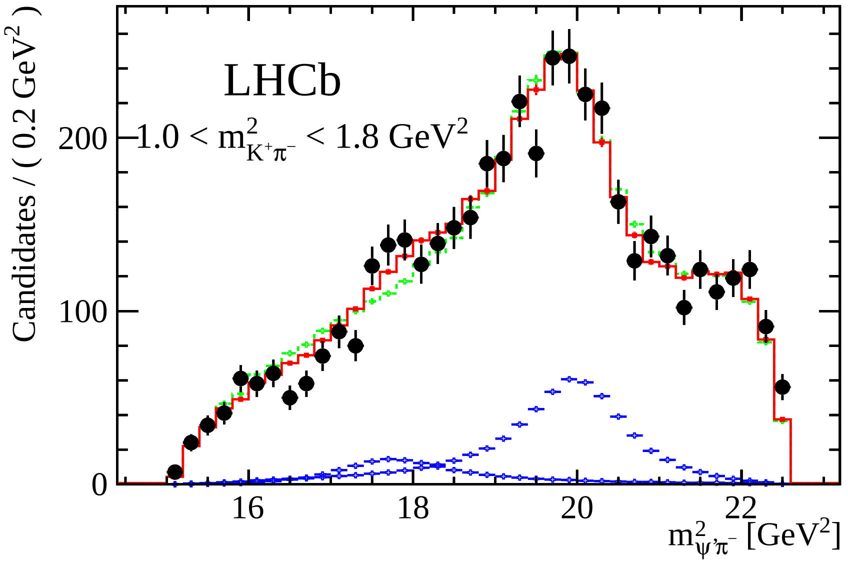


- Data are consistent with BW for $Z(4430)^+$
- But will they follow if BW is not imposed?
- Change BW in $Z(4430)^+$ amplitude to 6 complex numbers in 6 $M(\psi(2S)\pi)$ bins
- Plot resulting amplitude on Argand plot

$\Rightarrow$ It shows resonance behaviour without imposing it

Second Z^+ state

arXiv:1404.1903



$M(Z_0)$	$4239 \pm 18^{+45}_{-10}$ MeV
$\Gamma(Z_0)$	$220 \pm 47^{+108}_{-74}$ MeV
f_{Z_0}	$1.6 \pm 0.5^{+1.9}_{-0.4}$ %
$f^I_{Z_0}$	$2.4 \pm 1.1^{+1.7}_{-0.2}$ %
Significance	6σ

- Data can be described even better by adding second $\psi(2S)\pi$ state
- On its own, it is siginificant
- Prefered 0^- (but 660 ± 150 MeV wide 1^+ option cannot be ruled out)
- Argand diagram is inconclusive
- No evidence in model-independent approach
- Will need more data to clarify situation

Conclusions

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- Decay $X(3872) \to \psi(2S)\gamma$ seen with significance $4.4\,\sigma$
- Radiative $X(3872)$ decays inconsistent with pure molecule
- $Z(4430)^+$ from Belle confirmed and $J^P = 1^+$ without any doubts
- From Argand plot, resonance character of $Z(4430)^+$ is demonstrated
- Charge and quantum numbers rule out conventional explanations
- $Z(4430)^+$ most likely tetraquark state
- Really interesting era is ahead of us

Backup

LHCb detector

- Good mass resolution
- Good time resolution
- High trigger rate on c and b
- Uniform running conditions